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Shake table studies of seismic response of single partially supported piles

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ABSTRACT

An experimental investigation into the seismic response of soil-pile interaction has been carried out. Shake table tests have been conducted on single flexible model pile embedded in loose dry sand. Several parameters such as unsupported pile length, supported mass at the pile head, and intensity of applied base motion were examined experimentally in order to study their effects on the distribution and intensity of bending moments induced in each model pile. The natural frequency of the model pile was determined using two different techniques.

INTRODUCTION

Piles vibrate when supported structures are exposed to dynamic forces resulting from wind, waves, earthquakes, etc. Earthquake vibrations are transmitted through soil or rock into the structure generating dynamic stresses and displacements in structure and ground resulting in an extremely complex interaction problem. Use of pile foundations for supporting machines, off-shore platforms, and structures built in earthquake zones, requires a better understanding of dynamic behaviour of piles in order to produce more accurate and effective designs.

Over the past years, several analytical models have been developed. Many of these are based on either visco-elastic or Winkler type models (Flores-Berrones and Whitman 1982; Novak and Nagomai 1977; Novak et al. 1978; Kagawa and Kraft 1981). Some researchers have used three dimensional analysis to obtain dynamic pile response (Nogami et al. 1976; Baba et al. 1977; Neilson 1982). Others have adopted various numerical methods to treat the soil-pile interaction problem using discretized models (Kuhlemeyer 1976; Emery and Nair 1977; Baguelin and Frank 1980). While there have been a large number of analytical studies on dynamic response of piles, published records of experimental data are somewhat scarce (Finn and Gohl, 1987; Gohl and Finn, 1987; Steedman and Maheetharan, 1989; Stanton et. al 1988). Detailed measurements of the behaviour of prototype piles subjected to strong earthquake loading are also not yet available. The present experimental research therefore was undertaken to obtain experimental data against which the performance of theoretical models for predicting seismic response of single piles could be calibrated.

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EXPERIMENTAL PROGRAM

In the present experimental program, single flexible model piles embedded in loose dry sand were tested on a shake table under sinusoidal motion to simulate seismic loading on the soil-pile system. Bending strains induced in each model pile and accelerations at the base and at the pile head were recorded. Piezoceramic bender elements were used to monitor the distribution of shear wave velocity through the sand medium. Natural frequency of the model pile was also measured experimentally using techniques described by Gohl and Finn (1987).

The experimental study consisted of twelve small scale tests comprising four test series. Details of these tests are given in Table I. The objectives were to study the effects of the following parameters on dynamic response of single piles:

1. unsupported length of the model pile
2. supported mass at the pile head
3. magnitude and frequency of applied base acceleration

Test set-up

A schematic representation of the test set-up is shown in Figure 1. Motion of the shake table was controlled by a hydraulic actuator and feedback control. A rigid wooden sand container (495 mm x 1016 mm), diagonally braced to prevent any movement other than that of the shake table, was bolted to the shake table. Two 25mm thick styrofoam pads were placed at each end of the container to reduce effects of wave reflection from the sides of the box perpendicular to the direction of the base motion. An accelerometer was attached at the base of the sand container to measure input acceleration.

The model piles used in this study were made from hollow aluminium tubing with a wall thickness of 1 mm and an outside diameter of 6.35 mm. Ten calibrated single element gauges with gauge lengths of 3.175 mm (0.125 in) were installed at various elevations on the outside of the model pile. The flexural rigidity (EI) of the model pile was measured to be approximately 4.5×10^{6} N-mm^2 and its mass per unit length including the contributions of strain gauges and lead wires was found to be about 0.00028 kg/mm. The head mass with an attached accelerometer was clamped at the pile head. Strain gauge, accelerometer, and bender element signals were stored in a microcomputer using a data acquisition interface.

The instrumented pile was placed inside the model sand container and the foundation prepared using dry silica sand with an average void ratio of 0.65. A raining technique was used for sand placement. The sand container was filled several times prior to shake table studies to ensure that uniform and consistent sand beds were prepared.

Shear Wave Velocity of Sand Medium

Prior to the main series of tests on model piles using a shake table, shear wave velocity transmission in model sand bed was studied using bender elements. Three bender elements were placed inside the prepared sand bed at depths of 127 mm, 254 mm and 381 mm below finished sand surface to measure shear wave velocity. Each bender element consisted of a thin metal disc with a ceramic coating at the central area. The coating, which is extremely sensitive, generated electrical charge when excited by any kind of vibration. A shear wave vibration was generated by applying a horizontal shock load to a shear plate placed on top of the soil surface.

The average shear wave velocity for the top 381 mm sand layer was calculated to be 254 m/sec. This agrees with the data from Gohl and Finn (1987) who reported an average shear wave velocity of 211 m/sec for 300 mm thick dense Ottawa sand with an average void ratio of 0.57.

Natural Frequency of the Model Pile

Ringdown technique (Gohl and Finn 1987) was used to measure natural frequency of the model pile. In this method, the pile head was displaced a certain amount and then released so that it vibrated freely. Pile head acceleration was recorded as shown in Figure 2(a) for pile test C1 (Table 1). A Fourier spectrum shown in Figure 2(b) indicates a fundamental frequency of the pile to be about 4.2 Hz.

The same model pile (test C1) was subjected to a base acceleration of about 0.1g at different excitation frequencies. Maximum bending moment plotted against the different frequencies of base excitation is shown in Figure 2(c). This figure indicates that the pile has a resonant frequency of about 3 Hz. This is smaller than the value of natural frequency obtained from the ringdown test. It appears that when the pile was subjected to shake table motion, there was greater strain softening in sand caused by the high steady state response amplitudes thereby reducing the value of resonant frequency. Similar observations have been reported by Gohl and Finn (1987).

Test Procedure for Dynamic Pile Response

The shake table assembly was subjected to a sinusoidal base motion of approximately 0.1g at a starting frequency of 1 Hz which was gradually increased up to 9 Hz in test series A, B and C (Table 1). This procedure was adopted as only large amplitude shaking with peak acceleration amplitude of 0.5g with frequencies between 20 to 30 Hz resulted in significant sand densification. The base acceleration was maintained for 12 seconds at each frequency during which time signals from strain gauges and accelerometers were recorded at an interval of 0.01 second. This procedure was repeated in series D for base accelerations of 0.25g and 0.34 g.

EXPERIMENTAL RESULTS

Time history of acceleration applied at the base and recorded at the pile head was monitored in all the tests performed. The data indicated that the base acceleration was amplified by a factor of about 2 at the pile head. In the experimental data reported by Gohl and Finn (1987) on model piles in dense sand, the base acceleration of 0.6g was amplified to 3.5g at the pile head. Time history of bending moments at various depths along the pile is shown in Figure 3.

Distribution of bending moment along the pile length for different unsupported pile lengths and head masses are shown in Figures 4 (a) and (b) respectively. These figures indicate that pile bending moment increases linearly from the top of the pile to the soil surface and then from there decreases nonlinearly to zero at greater depths. Maximum bending moments occurred approximately 12 pile diameters below the soil surface when the pile was almost fully embedded. Gohl and Finn (1987) have reported under similar loading conditions that maximum bending moment occurs approximately 13 pile diameters below the soil surface. The common trend of distribution of bending moment along pile length indicated that the pile displacements and bending moments reduce to negligible values after a depth of about 30 pile diameters below the soil surface. Similar observations have also been reported by Gohl and Finn (1987) for fully embedded piles.

A summary of experimental results of the study presented herein is given in Table 2. The results show that maximum bending moments induced in the pile increase with increased unsupported length of the pile, head mass at the pile top, and the base accelerations. Within the range of parameters studies the magnitude of head mass at the pile top appears to have maximum effect on the bending moments in the pile.

CONCLUSIONS

The magnitude and distributions of shear moduli in the sand medium was determined using piezoceramic bender elements. This procedure was found to produce reliable results which can be used in calibrating the present experimental work with analytical predictions.

The procedures proposed by Gohl and Finn (1987) were used for the determination of fundamental natural frequency of the pile. The results confirmed the earlier findings by others that the frequency sweep tests yield reduced natural frequency values due to cyclic strain sorting of the soil around the pile.

Lateral pile response to sinusoidal base accelerations indicated that the model piles vibrated mainly in the first mode. The parametric study of piles subjected to sinusoidal base motion input showed that the peak bending moments increased with increase in unsupported length, head mass at the pile top, and the amplitude of base accelerations.

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TABLE I
Summary of Experimental Program

Test Series	Test Number	Pile Length (mm)	Unsupported Length (mm)	Head Mass (kg)	Exciting Frequency (Hz)	Base Acc. (g)
A	A1	610	40	0.79	1 to 9	0.14
	A2	610	152	0.79	1 to 9	0.12
	A3	610	304	0.79	1 to 9	0.14
C	B1	610	40	0.45	1 to 9	0.12
	B2	610	40	0.79	1 to 9	0.14
	B3	610	40	1.13	1 to 9	0.14
C	C1	305	40	0.79	1 to 9	0.13
	C2	610	40	0.79	1 to 9	0.14
	C3	915	40	0.79	1 to 9	0.15
D	D1	305	40	0.79	3	0.16
	D2	305	40	0.79	3	0.25
	D3	305	40	0.79	3	0.34

Table 2: Summary of Experimental Results

Test Number	Pile Length (mm)	Unsupported Length (mm)	Head Mass (kg)	Exciting Frequency (Hz)	Base Acc. (g)	Maximum B.M. (N-mm)
(a) Effect of unsupported length						
A1	610	40	0.79	2.7	0.18	211.1
A2	610	152	0.79	2.7	0.11	283.6
A3	610	304	0.79	2.7	0.15	300.7
(b) Effect of Magnitude of Head Mass:						
B1	610	40	0.45	2.7	0.13	174.8
B2	610	40	0.79	2.7	0.13	310.0
B3	610	40	1.13	2.7	0.15	534.8
(c) Effect of Base Acceleration:						
D1	305	40	0.79	3.0	0.16	300.2
D2	305	40	0.79	3.0	0.25	352.9
D3	305	40	0.79	3.0	0.34	451.8

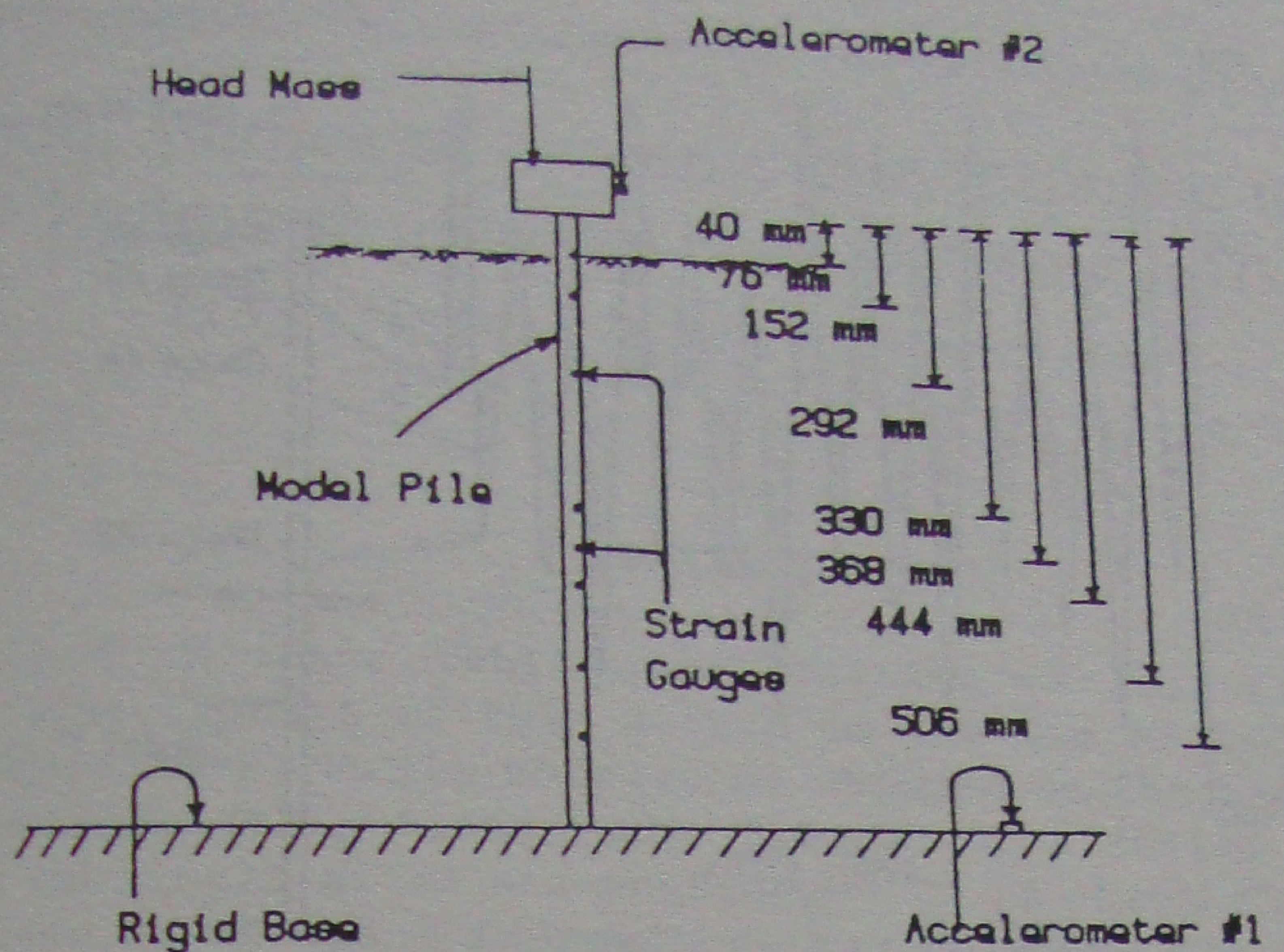

Fig. 1. Experimental Set-Up

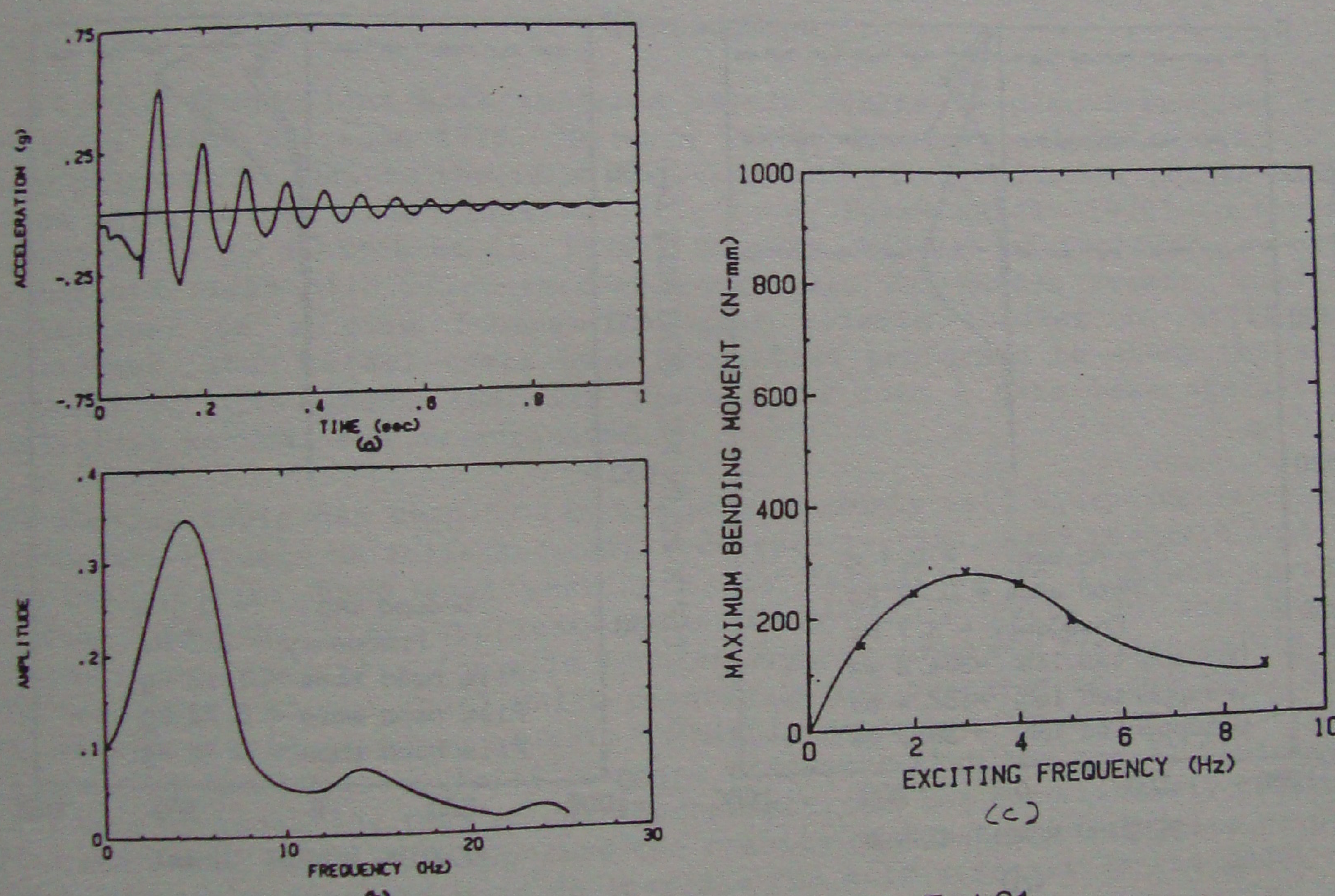

Fig. 2. Natural Frequency of Model Pile, Test C1
(a) and (b) Ring Down Test (c) Frequency Sweep Test

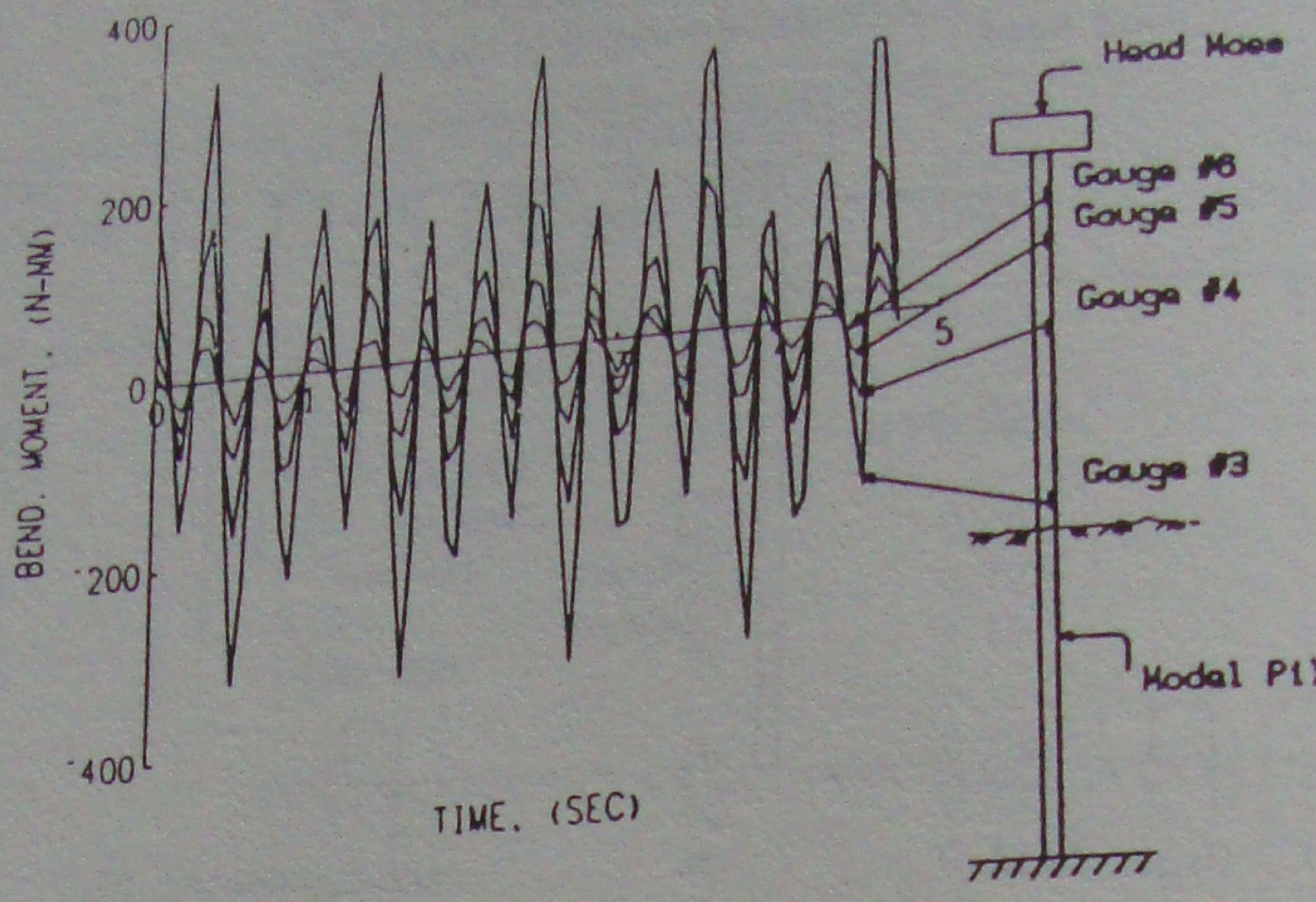

Fig. 3. Time History of Bending Moments (Test A3, Exciting Frequency 1Hz)

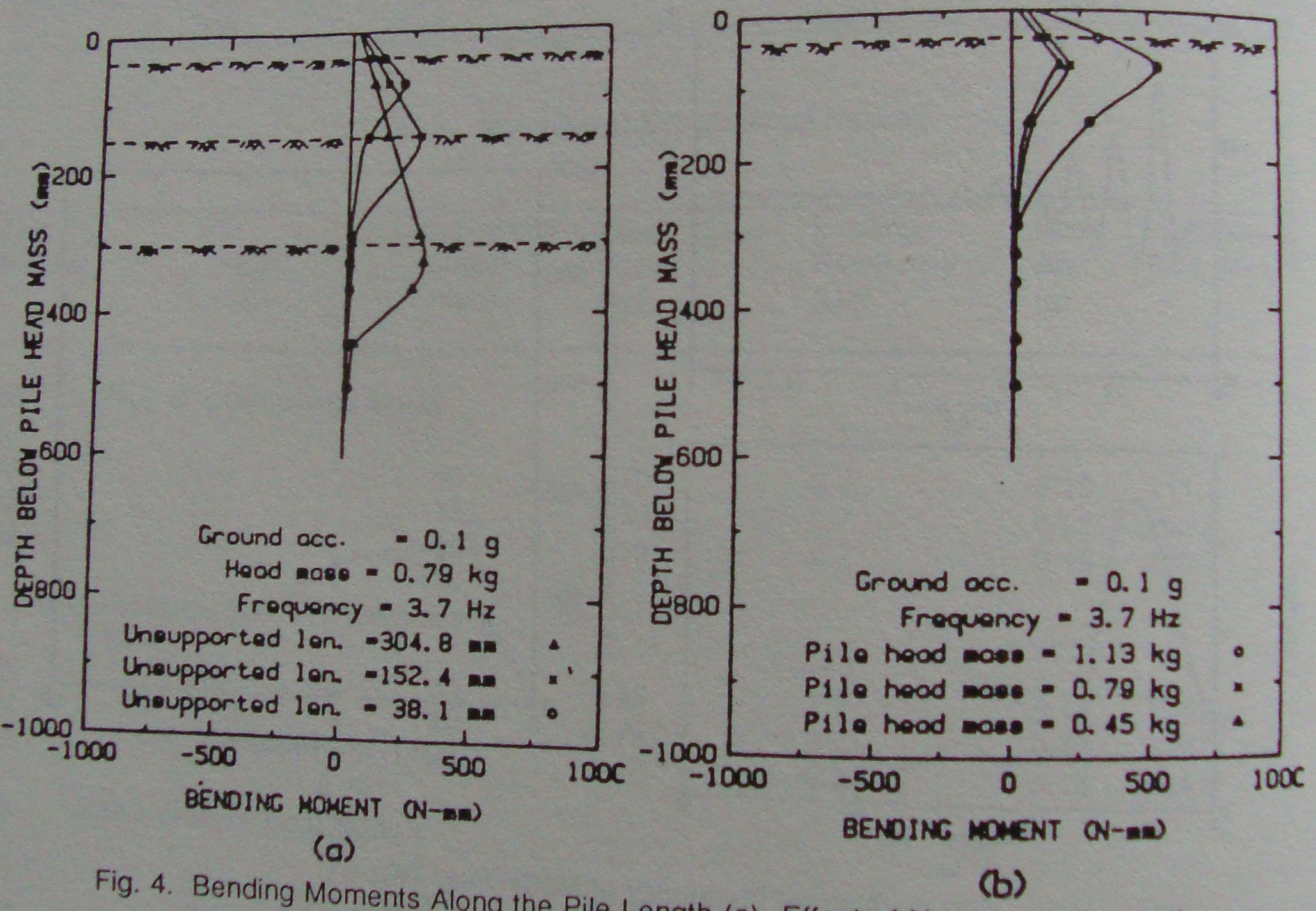

Fig. 4. Bending Moments Along the Pile Length (a) Effect of Unsupported Length (b) Effect of Pile Head Mass